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Corrosion of Dental Magnet Attachments for Removable Prostheses on Teeth and Implants

Arne F. Boeckler, DMD, Dr Med Dent,[1] Carolin Ehring, DMD,[1] Dean Morton, BDS, MS,[2]
Jürgen Geis-Gerstorfer, Dr Rer Nat, Dipl Ing,[3] & Juergen M. Setz, DMD, PhD, Dr Med Dent Habil[1]

[1] Department of Prosthodontics, Martin-Luther University Halle-Wittenberg—Center for Dentistry and Oral Medicine, Germany
[2] Department of Oral and Maxillofacial Surgery and Diagnostic Sciences, Center for Implant Dentistry, University of Florida, Gainesville, FL
[3] Department of Medical Materials and Technology, University Hospital Tuebingen—Center for Dentistry and Oral Medicine, Germany

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Correspondence
Arne Boeckler, Martin-Luther-University Halle-Wittenberg—Centre for Dentistry and Oral Medicine, Department of Prosthodontics, Grosse Steinstr. 19 Halle (Saale) 06108, Germany. E-mail: arne.boeckler@medizin.uni-halle.de

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Abstract

Purpose: For a long time, the use of magnets for the anchorage of dental prostheses failed due to lack of biocompatibility and the magnets' high susceptibility to corrosion in the mouth. These facts make encapsulation of the magnetic alloy with a corrosion-resistant, tight, and functionally firm sealing necessary. Due to different products and analysis methods, it is not feasible to compare the findings for contemporary products with the sparse and rather old test results in the literature. Therefore, the aim of this study was the standardized control and the comparison of the corrosion behavior of modern magnetic attachments for use on teeth and dental implants.

Materials and Methods: Thirty-seven components of magnetic attachments on implants and natural teeth from different alloys (NdFeB, SmCo, Ti, CrMoMnTiFe, etc.) as delivered by the manufacturers or fabricated according to their instructions were examined for their corrosion behavior using the statical immersion analysis (ISO 10271:2001). Four specimens of every product with the same design were used. An uncased SmCo magnet served as control. Analyses after 1, 4, 7, and 28 days of the storage in corrosion solution were made. The eluate was examined quantitatively on the alloy components of the respective component with the help of optical emission spectrometry (μg/cm^2). The results were compared to the requirements of ISO standard 22674:2006. In addition, existing corrosion products were also defined in the solution after 28 days. The results were analyzed descriptively and statistically to determine possible significant differences (*t*-test and Mann-Whitney-Wilcoxon rank-sums test; $p < 0.05$).

Results: Dissolved metal ions could be found on all tested products. The release after 1 and 4 days was different for all specimens. In the group of implant abutments, the highest ion release after 7 days was found (all measurements μg/cm^2): Fe (13.94, Magfit-IP-IDN dome type), Pd (1.53, Medical-anchor), Cr (1.32, Magfit-IP-IDN dome type), Ti (1.09, Magfit-IP-IDN abutment), Co (0.81, Medical-anchor), and B (0.6, Magfit-IP-IDN dome type). After 28 days, the analyzed ion release increased irregularly: Fe (173.58, Magfit-IP-IDN dome type), Pd (44.17, Medical-anchor), Cr (2.02, Magfit-IP-IDN dome type), Ti (2.11, Magfit-IP-IDN abutment), Co (26.13, Medical-anchor), B (1.77, Magfit-IP-IDN dome type), and Nd (79.18, Magfit-IP-IDN dome type). In the group of magnetic systems on natural teeth, the highest ion release after 7 days was found for Fe (4.81, Magfit DX 800 keeper), Cr (1.18, Magfit DX 800 keeper), Pd (0.21, Direct System Keeper), Ni (0.18, WR-Magnet S3 small), Co (0.12, Direct System Keeper), and Ti (0.09, Magna Cap – Mini). After 28 days, the analyzed ion release increased non-uniformly: Fe (31.92, Magfit DX 800 Keeper), Cr (6.65, Magfit DX 800 Keeper), Pd (18.19, Direct System Keeper), Ni (0.61, WR-Magnet S3 small), Co (10.94, Direct System Keeper), Ti (0.83, Magna Cap – Mini), and Pd (2.78, EFM Alloy). In contrast, the uncased control magnet showed an exponential release after 7 days of Sm ions (55.06) and Co-ions (86.83), after 28 days of Sm ions (603.91) and Co ions (950.56). The release of corrosion products of all tested products stayed significantly under the limit of 200 μg/cm^2 (ISO 22674:2006). In contrast, the non-encapsulated control magnet exceeded that limit significantly.

Conclusion: The analysis of the corrosion behavior of modern magnetic attachments for use on teeth and dental implants according to ISO 10271:2001 showed that metal ions had dissolved on all specimens. In the case of one product, the magnet corroded. For this product, an improvement of the capsulation would be desirable. None of the products reached the limit specified in ISO 22674:2006. All products seem to be suitable for dental application. Further studies in regard to the specific biocompatibility and possible cytotoxic effects on mucosa and tissue would be desirable.

Regarding the retention of dental prostheses on implants and roots of the teeth, dental magnetic systems are an alternative for bar or spherical anchor attachments.[1-6] As shown in in vivo[7,8] and in vitro studies,[9,10] one advantage to the use of magnetic attachments is the loss of magnetic anchorage in the presence of high forces, so that overstressing of the abutment teeth or implants is avoided. Another advantage can be seen using this method as a comparatively simple prosthetic treatment option with non-parallel implants.[11-13]

Normally, such a magnetic system consists of a magnet fixed in the denture base and a corresponding magnetic attachment that has either the form of a post with a dome on top to cover the remaining root (keeper) or of an implant abutment. These corresponding anchors are made of either a soft ferro-magnetic alloy, which can easily be magnetized and have no static magnetic field of their own,[14] or a static magnet placed permanently in the mouth. In such systems, rare earth magnets made of samarium-cobalt (SmCo) or neodym-iron-boron (NdFeB) alloys are used.[13,15]

For a long time, experiments using magnets for the anchorage of dental prostheses failed due to lack of biocompatibility and the magnets' high susceptibility to corrosion in the mouth.[16] This fact makes encapsulation of the magnetic alloy with a corrosion-resistant, tight, and functionally firm sealing necessary.[17]

The corrosion properties of an alloy, and thus its biocompatibility, depend on the alloy composition and the structure of the single metallic elements within this alloy. The release of elements, and thus the physical reaction to the corrosion, are defined by the interaction between the biological milieu of the mouth and the phase structure of the alloy components.[18,19] Corrosion is defined as gradual deterioration of material by chemical processes, such as oxidation, or attack by acids. Of great significance is the corrosion due to the combined effects of temperature, humidity, and micro flora in the oral cavity.

In the past, metallic corrosion was tested in different ways. For example, corrosion was analyzed visually by examining the surface of the specimen, by determining the surface roughness and the loss of weight, or by indirect, electrochemical measurement of the electron flow and the release of elements.[19-22] Other authors used changes in the magnetic flux density or in the retention force for determining the amount of corrosion.[23,24] Another option is the direct, quantitative measurement and identification of released elements with the help of different analytical methods.[18,22,25-27] In these experiments, different solutions were used as the corrosive medium.[22-24,28,29]

The limit value for the metal ion release of metallic materials in the mouth is described in ISO 22674:2006 "Metallic materials for fixed and removable restorations and appliances." The standard is that metal ion release shall not exceed 200 μg/cm^2.

Corrosion taking place in the mouth can be perceived subjectively by the patient. Sometimes, the products of the corroded metals are visibly embedded in the gingiva around the prosthesis. Corrosion products flowing out of the reaction medium into the organism can cause tissue reactions. Persistent corrosion can lead to an irregular wear of the metal. As a result, the components of the alloy dissolve as charged ions. Corrosion processes on abutments have also been associated with the failure of implants. Compared to the peripheral bone, the peri-implant bone shows a higher concentration of metallic corrosion products.[30]

The qualitative evidence of alloy components in local tissue and more distantly in blood and urine allows no conclusions on the quantity of the released ions in the biological milieu. For this reason, it is not possible to make any conclusions about possible toxicological side effects or to calculate the quantity of damage.

Samarium-cobalt (SmCo) magnets, implanted into the abdominal wall of rats, were found encapsulated in fibrous tissue without macroscopic abnormalities of the surrounding tissue.[31] In other studies, neodymium-iron-boron (NdFeB) magnets showed no influence on the cellular proliferation of osteoblasts.[31-33] In one study, a cytotoxic effect of the corrosion products of NdFeB magnets on mouse fibroblasts and on fibroblasts of human cheek mucosa could be demonstrated according to ISO 7405.[26,34] Fe ions and $NdCl_3$ ions were defined as the most prominent corrosion products.

The cytotoxic potential of NdFeB magnets and SmCo magnets has also been documented in micropore filter and extraction analyses.[29,33,35] In this process, differences were found in the cytotoxic potential of the uncased magnets. Capsulation of the magnets in titanium made the specimen nontoxic.[27]

The first trials to protect the magnetic alloy against corrosion were carried out with a Proplast coating, which is a mixture of polytetrafluorethylene (PTFE) and graphite. These have not been corrosion protective in the long run.[14] Other tests were made by using epoxide resins,[36] stainless steel,[37] and parylene,[29] a corrosion-protective polymeric coating material applied in vacuum by condensation from gas phase as a nonporous and transparent polymer film on the magnet.[23,38]

There was also no sufficient corrosion protection in the case of magnets inserted in their capsule only via press fit.[22]

With the development of a special manufacturing technology where the magnet susceptible to corrosion is encased into a gas-tight, biocompatible titanium cover using laser welding technology, a satisfactory corrosion stability was achieved.[22] SmCo magnets encased that way had a significantly lower cytotoxic effect than did uncased magnets.[33]

Studies on dental magnetic systems show that corrosion properties are especially dependent on the tightness of the capsule and the corrosion stability of capsule, abutment, and keeper alloys.[22,39] The presence of particular bacteria like *Streptococcus sanguis* or a biofilm consisting of different bacteria also intensified the corrosion of NdFeB magnets, which was prevented by a parylene coating.[19,40] The corresponding magnetic attachments were especially susceptible to corrosion when they were screwed with a gap on the implant abutments.[21,22] The use of drills or permanent tilting of the prostheses over the abutments, which can cause ongoing wear, can also lead to the perforation of the capsule and thus to the exposure of the magnet.[6]

Comparative studies on the corrosion behavior of NdFeB magnets and SmCo magnets showed a significant influence, depending on the type of capsule.[22] Magnetic systems with welded titanium covers and pressed capsules made of an FeCrMo alloy with their respective corresponding ferromagnetic attachments were tested with the help of a gap corrosion test in ferric chloride solution (10%), sodium chloride solution (0.9%), and in artificial saliva. After 100 days, the electrolytes were analyzed quantitatively and qualitatively with the help of atom absorption spectrometry. In this analysis, no relevant corrosion products were found when using the titanium capsules. No parts of the magnetic alloy were detected; this exhibits the tightness of the welded cover. The FeCrMo capsules showed noticeable corrosive changes in artificial saliva and severe corrosive changes in ferritic chloride. All corresponding ferromagnetic attachments and keepers corroded considerably.

The necessity of encasing NdFeB and SmCo magnets was also demonstrated by a study in the course of which the specimens stayed in different corrosive solutions [NaCl (1%), lactic acid solution (1%), HCl (0.05%), Na_2S (0.1%), and artificial saliva] at 37°C for 2 days. The immersion in lactic acid solution and HCl resulted in severe corrosion and a high retention loss of the magnets.[41]

Magnetic alloys made of PtFeNb showed the same behavior as surgical stainless steel after corrosion tests in the electron microbeam analysis—EPMA.[25]

When comparing the corrosion behavior of uncased FePt magnets and NdFeB magnets, the retention behavior of the magnets to corresponding keepers made of stainless steel served as an indicator for the degree of corrosion.[24] The magnets were incubated in three corrosion media with different pH values [lactic acid solution (1%, pH = 2.7), sodium sulfite solution (0.1%, pH = 12), and artificial saliva (pH = 6.8)] at 37°C. The retention measurements were made after 28 and 60 days. After 7 days, the NdFeB magnets had completely dissolved in the lactic acid solution. Storing in sodium sulfite solution led to a reduction of 33% after 28 days and of 58% after 60 days. Storing in artificial saliva resulted in a reduction of 10% and 31% for 28 and 60 days, respectively. The FePt magnets showed better corrosion properties than did NdFeB magnets.

After 4 weeks of mechanical stress in a saline solution, the magnetic flux density of NdFeB magnets encased by Teflon and parylene was compared to the magnetic flux density of uncased NdFeB magnets.[23] At first, the magnetic flux density of the encased magnets was reduced, but after mechanical aging in a saliva solution, the encased magnets had a significantly higher flux density than the uncased magnets. Iron ions could be identified in the solution for all magnets.

The corrosion stability of ferromagnetic PdCo alloys in contact with SmCo magnets with different capsules was measured with a similar setup.[28] The results showed clear corrosion effects on the corresponding PdCo alloy.

Clinical follow-up examinations of 60 magnetic attachments revealed that 68% of the keepers on natural teeth and 100% of the implant abutments showed discoloration and clinical signs of corrosion after 24 months in use.[21]

By undertaking a review of the literature, it was discovered that because of the different magnetic systems, magnetic alloys, and capsules, the different test conditions and the nonstandardized analyzing methods, it is almost impossible to compare test results. Studies that tested the corrosion behavior of dental magnetic systems according to the standardized procedure defined in the ISO standard 10271:2001 "Dental metallic materials—Corrosion test methods" could not be found. Therefore, the aim of this study was the standardized control and comparison of the corrosion behavior of modern magnetic attachments for use on teeth and dental implants.

Materials and methods

Twenty-one components of magnetic attachments on implants (abutments and denture magnets, Table 1), and 16 components of magnetic attachments for the use on roots of natural teeth (cast root keeper, prefabricated root keeper, and denture magnets, Table 2) were examined for their corrosion behavior. The rare earth magnets used in the products were made of SmCo or NdFeB alloys. These magnets were all encapsulated in laser-welded containers. The corresponding ferromagnetic components consisted of palladium-containing alloys or ferritic stainless steel. All tested products were provided by the respective manufacturers. The specimens constructed from ferromagnetic cast alloys were produced in compliance with the manufacturers' instructions.

To comply with standardized conditions, corrosion behavior was examined using the statical immersion analysis according to ISO 10271:2001 "Dental metallic materials—Corrosion test methods." In this method, the maximum ion release after 7 days is subject to the individual surface for metallic materials in the mouth, limited to no more than 200 $\mu g/cm^2$ by ISO standard 22674:2006.

The preparation of specimen and test solution was carried out in compliance with the corrosion test methods for dental metallic materials. Each of the examined products consisted of a prosthesis magnet and a corresponding implant abutment or root keeper. For the examination, four specimens of every product with the same design were used. An uncased SmCo

Table 1 Magnetic implant attachments and detected elements after corrosion analyses

Manufacturer	Product implant abutment/ denture magnet	Rare earth magnet	Ferro-magnetic alloy/capsule/ abutment alloy (given by manufacturer)	Capsule sealing	Surface of abutment/ denture magnet (cm^2)		Detected elements day				
							1	4	7	28	Total
							($\mu g/cm^2$)				
Aichi (Tokyo, Japan)	Magfit-IP-IDN abutment		CrMoTiMnC : Febal (AUM 20)		5.73	Cr	0.18	0.49	0.21	1.66	2.54
						Fe	1.73	2.55	1.05	9.02	14.4
						Ti	0	0.08	1.01	1.02	2.11
	Magfit-IP-IFN abutment		CrMoTiMnC : Febal (AUM 20)		4.84	Cr	0.19	0.53	0	0.88	1.6
						Fe	1.44	2.56	0.38	4.48	8.86
						Ti	0	0.11	0.13	1.07	1.31
	Magfit-IP-IDN dome type	NdFeB	CrMoTiMnC : Febal (AUM 20)	Laser welded	5.73	Cr	0.11	0.49	0.72	0.7	2.02
						Fe	1.17	5.25	7.52	160	174
						Nd	0	0	0	79.2	79.2
						B	0.4	0.12	0.08	1.17	1.77
	Magfit-IP-IFN flat type	NdFeB	CrMoTiMnC : Febal (AUM 20)	Laser welded	4.98	Cr	0.14	0.5	0.44	3.51	4.59
						Fe	0.73	2.5	2.03	16.5	21.7
Brasseler (Lemgo, Germany)	MicroPlant Primary anchor	NdFeB	Ti	Laser welded	5.65	Ti	0	0.05	0	0.41	0.46
	MicroPlant Secondary anchor	NdFeB	Ti	Laser welded	8.85	Ti	0.05	0.14	0.1	0.7	0.99
Dyna (Bergen op Zoom, The Netherlands)	Medical-anchor		PdPtCo		6.28	Pd	0.12	0.57	0.84	42.6	44.2
						Co	0.16	0.31	0.34	25.3	26.1
	WR-Magnet S3 small	NdFeB	CoCrNiMo : Febal	Laser welded	5.98	Cr	0.1	0.16	0	0.66	0.92
						Fe	0.51	0.66	0.15	2.66	3.98
						Ni	0.07	0.11	0	0.43	0.61
	WR-Magnet S5 standard	NdFeB	CoCrNiMo : Febal	Laser welded	7.46	Cr	0.07	0.12	0	0.55	0.74
						Fe	0.37	0.49	0.17	2.23	3.26
						Ni	0.05	0.08	0	0.37	0.5
Steco (Hamburg, Germany)	X-Line Titanmagnetics Insert	SmCo	Ti	Laser welded	9.65	Ti	0	0.06	0	0.5	0.56
	Z-Line Titanmagnetics Insert	SmCo	Ti	Laser welded	7.62	Ti	0	0.05	0	0.38	0.43
	K-Line Titanmagnetics Insert	SmCo	Ti	Laser welded	15.31	Ti	0	0.06	0	0.45	0.51
	X-Line Titanmagnetics	SmCo	Ti	Laser welded	11.02	Ti	0	0.7	0.7	0.9	2.3
	Z- Line Titanmagnetics	SmCo	Ti	Laser welded	12.42	Ti	0	0.05	0	0.64	0.69
	K-Line Titanmagnetics	SmCo	Ti	Laser welded	12.42	Ti	0	0.07	0.6	0.73	1.4
Technovent (Leeds, U.K.)	Magnabutment – Mini		CoCrTiNiMo : Febal		5.94	Fe	0.06	0	0	0	0.06
						Ti	0	0.12	0.08	1.53	1.73
	Magnabutment – Maxi		CoCrTiNiMo : Febal		6.72	Fe	0.63	0	0	0	0.63
						Ti	0	0.12	0.08	1.53	1.73
	Magna Cap – Micro	NdFeB	CoCrTiNiMo : Febal	Laser welded	7.71	Fe	0.27	0.06	0	0.08	0.41
						Ti	0	0	0	0.2	0.2
	Magna Cap – Mini	NdFeB	CoCrTiNiMo : Febal	Laser welded	7.45	Fe	0	0	0	0.28	0.28
						Ti	0.09	0	0	0.74	0.83
	Magna Cap – Midi	NdFeB	CoCrTiNiMo : Febal	Laser welded	10.28	Fe	0.08	0	0	0	0.08
						Ti	0	0	0	0.44	0.44
	Magna Cap – Maxi	NdFeB	CoCrTiNiMo : Febal	Laser welded	11.5	Fe	0.08	0	0.09	0.54	0.71
						Ti	0	0	0	0.18	0.18
	Sample	SmCo		Unsealed	12.56	Sm	0.16	11.8	43.1	549	604
						Co	0.23	18.9	67.7	874	961

magnet served as a control specimen (Table 1). In contrast to ISO 10271:2001, where examination after storage in corrosion solution for only 7 days is described, in this study, additional analyses after 1, 4, and 28 days of storage in corrosion solution were made to examine a possible dependence on time.

Before the examination, all specimens were cleaned in an ultrasonic bath containing ethanol for 2 minutes. Afterward

Table 2 Magnetic attachments on teeth and detected elements after corrosion analyses

Manufacturer	Product keeper/ insert/ magnetic alloy/ denture magnet	Rare-earth magnet	Ferro-magnetic alloy capsule/ keeper alloy (given by manufacturer)	Capsule sealing	Surface of keeper/ denture magnet (cm^2)		Detected elements day				
							1	4	7	28	Total
							($\mu g/cm^2$)				
Aichi (Tokyo, Japan)	Magfit DX 400 Keeper		CrMoTiMnC : Febal (AUM 20)		1.88	Fe	0.24	0.12	0	0.21	0.57
	Magfit DX 600 Keeper		CrMoTiMnC : Febal (AUM 20)		3.02	Fe	0.25	0.05	0	0.13	0.43
	Magfit DX 800 Keeper		CrMoTiMnC : Febal (AUM 20)		2.83	Fe	0.82	2.42	1.57	27.11	31.92
						Cr	0.13	0.59	0.46	5.47	6.65
	Magfit DX 400	NdFeB	CrMoTiMnC : Febal (AUM 20)	Laser welded	4.02	Fe	0.42	0.16	0.09	0.21	0.88
	Magfit DX 600	NdFeB	CrMoTiMnC : Febal (AUM 20)	Laser welded	3.52	Fe	0.29	0.18	0.06	0.22	0.75
	Magfit DX 800	NdFeB	CrMoTiMnC : Febal (AUM 20)	Laser welded	4.84	Fe	0.5	0.19	0.05	0.26	1
Dyna (Bergen op Zoom, The Netherlands)	Direct-System-Keeper		PdPtCo		7.16	Pd	0	0.11	0.1	17.98	18.19
						Co	0.05	0.07	0	10.82	10.94
	EFM Alloy		PdPtCo		5.66	Pd	0	0	0	2.78	2.78
						Co	0.09	0	0	2.05	2.14
	WR-Magnet S3 small	NdFeB	CoCrNiMo : Febal	Laser welded	5.98	Cr	0.1	0.16	0	0.66	0.92
						Fe	0.51	0.66	0.15	2.66	3.98
						Ni	0.07	0.11	0	0.43	0.61
	WR-Magnet S5 standard	NdFeB	CoCrNiMo : Febal	Laser welded	7.46	Cr	0.07	0.12	0	0.55	0.74
						Fe	0.37	0.49	0.17	2.23	3.26
						Ni	0.05	0.08	0	0.37	0.5
Technovent (Leeds, U.K.)	Insert Keeper – Mini		CoCrTiNiMo : Febal		4.15	Fe	0.05	0	0	0.06	0.11
	Insert Keeper – Maxi		CoCrTiNiMo : Febal		5.37	Fe	0.14	0	0	0.07	0.21
	Post Keeper – Mini		CoCrTiNiMo : Febal		5.67	Fe	0.38	0.13	0.15	0.24	0.9
						Cr	0	0	0.05	0	0.05
	Post Keeper – Maxi		CoCrTiNiMo : Febal		7.8	Fe	0.4	0.27	0.27	0.23	1.17
						Cr	0	0.8	0.1	0.1	1
	Magna Cap – Mini	NdFeB	CoCrTiNiMo : Febal	Laser welded	7.71	Fe	0	0	0	0.28	0.28
						Ti	0.09	0	0	0.74	0.83
	Magna Cap – Maxi	NdFeB	CoCrTiNiMo : Febal	Laser welded	11.49	Fe	0.08	0	0.09	0.54	0.71
						Ti	0	0	0	0.18	0.18

they were washed with distilled water and dried with oil- and water-free compressed air. Since there are often traces of rare-earth elements in glass test tubes, polypropylene test tubes (TPP, Trasadingen, Switzerland) were used to avoid contamination by the used test tubes and thus a falsification of the results. Each specimen was put into a single, sterile polypropylene tube. The corrosion solution was freshly prepared for every test interval. To make the solution, 10.0 g of 90% lactic acid and 5.85 g of common salt were dissolved in 300 ml of distilled water and then diluted with water up to 1000 ml. Test solutions with a pH value other than 2.3 (±0.1) were rejected. The extraction was made in consideration of a surface/volume ratio of 1 cm^2/ml of the test solution. The manufacturers' instructions regarding the technical size of the axially symmetrical specimens were used as the basis for calculating the respective surface (Tables 1, 2). To avoid evaporation of the solution, the specimens were closed and incubated in an incubator at 37°C (±1°C). After every interval, the specimens were taken out of the corrosion solution with a nonmetallic pair of tweezers, washed with distilled water, air-dried, and put into a new tubule with a fresh test solution for incubation.

The eluate/solution was examined quantitatively on the alloy components of the respective implant abutment, root keeper, or denture magnet as they are defined by the manufacturer with the help of optical emission spectrometry (ICP-spectrometer Optima 4300DV, Perkin Elmer, Waltham, MA). The lower limit of determination for the found ions amounted to 0.05 μg/ml. The results were compared to the requirements of ISO standard 22674:2006. In addition to the specifications of the ISO standard, existing corrosion products were also defined in the solution after 28 days.

The results were analyzed descriptively and statistically to determine possible significant differences (t-test, Mann-Whitney, Wilcoxon rank sums test; $p < 0.05$).

Results

In the groups of implant abutments (Table 1), the root keepers (Table 2), and the corresponding denture magnets, dissolved metal ions could be found on all specimens. But not all alloy components of the respective implant abutment, root keeper, or denture magnet defined by the manufacturer could be found dissolved in the corrosive solution. So, only elements with content over the minimum detection threshold of the used analytical optical emission spectrometry were recorded.

In the case of magnetic systems on implants Magfit-IP-IDN dome type showed the highest release among the prosthesis magnets amounting to 13.94 μg/cm^2 (Fe ions) after 7 days, and the Magfit-IP-IDN abutment showed the highest release among the implant abutments amounting to 5.33 μg/cm^2 (Fe ions). B ions were also found for this product (0.6 μg/cm^2).

Magfit-IP-IDN dome type had, with 173.58 μg/cm^2 (Fe ions), the highest release of corrosion products among the prosthesis magnets after 28 days. B ions (1.77 μg/cm^2) and, contrary to the measurement after 7 days, Nd ions (79.18 μg/cm^2) could also be found here. In regard to the implant abutments, the Medical-anchor product had the highest corrosion ratio amounting to 44.17 μg/cm^2 (Pd ions).

When measuring the products with capsules made of alloys from titanium or titanium and stainless steel after 1 and 4 days, no or only minor release of metal ions could be found in most cases. These products had the lowest amount of corrosion products after 7 days and also after 28 days. In regard to the other products, there was a noticeable release of Fe ions on the first day. When comparing the release of corrosion products after 7 days and after 28 days of storing in the corrosion media, it was evident that the denture magnet Magfit-IP-IDN dome type had the highest exponential increase (Fe ions), but also the largest decrease (Cr ions). In the group of implant abutments, the Medical-anchor had the highest increase of release (Pd-ions), whereas the largest decrease in the release could be found with Magfit-IP-IFN Abutment (Fe ions).

In regard to the magnetic systems on natural teeth (Table 2), the product WR-Magnet S3 small showed the highest release of all products among the denture magnets, with 1.32 μg/cm^2 (Cr ions) after 7 days, and the Magfit DX 800 Keeper had the highest release among the keepers with 4.81 μg/cm^2 (Fe ions).

With an amount of 31.92 μg/cm^2 (Fe ions), the Magfit DX 800 Keeper had the highest release of corrosion products among the denture magnets after 28 days. Among the implant abutments, the highest total corrosion ratio amounted to 3.26 μg/cm^2 (Fe ions) with WR-Magnet S5 standard, and 0.61 and 0.5 μg/cm^2 (Ni ions) was measured with the products WR-Magnet S3 small and WR-Magnet S5 standard, respectively.

Also in the case of magnetic systems on natural teeth, the lowest amounts of corrosion products were for products with caps made of titanium or alloys of titanium and stainless steel after 7 days, as well as after 28 days. While Fe ions were released after the first day, the Ti ions could often be found only after 28 days in the eluate/solution.

When comparing the release of corrosion products after 7 days and after 28 days, the denture magnet WR-Magnet S3 small had the highest exponential increase (Ni ions), but also the largest decrease (Fe ions). In the group of the keepers, the highest increase of the release was with Magfit DX 800 Keeper (Fe ions), while the release decreased clearly in the case of Post Keeper-Maxi (Fe ions).

In the case of the uncased SmCo magnet used as control, corrosion products dissolved from the first day on (Table 1). After 7 days, there was a clear release of Sm ions (55.06 μg/cm^2) and Co ions (86.83 μg/cm^2). After 28 days, an exponential increase of the amount of released corrosion products of 603.91 μg/cm^2 (Sm ions) and 960.83 μg/cm^2 (Co ions) could be found.

During the statistical comparison of the corrosion product released after 1, 4, 7, and 28 days, no significant differences were found (Mann-Whitney, Wilcoxon rank-sums test; $p <$ 0.05) for the single products or for a comparison between the products.

A comparison of the released amount of corrosion products with ISO standard 22674:2006 for maximum ion release after 7 days showed that the limit of 200 μg/cm^2 was reached by none of the tested products. All values stayed significantly under this limit (*t*-test, Mann-Whitney, Wilcoxon rank-sums test; $p < 0.05$). Only the nonencapsulated control magnet clearly exceeded that limit ($p = 0.00$).

Discussion

To make a statement on the biocompatibility of an alloy, it is important to identify the quality and quantity of the elements released by corrosion. Metallic corrosion and the associated release of ions are often the reason for harmful effects like toxicity and sensitization. What counts is the kind and amount of released elements, as well as the duration of exposition.[18] For dental alloys, the determination of corrosion products is defined in ISO standard 10271:2001 "Dental metallic materials—Corrosion test methods." In ISO standard 22674:2006 the limit for maximum ion release after 7 days was defined as 200 μg/cm^2, subject to the individual surface.

The comparison of the released amount of corrosion products with the specifications in ISO standard 22674:2006 showed that none of the analyzed products reached the limit of 200 μg/cm^2 after 7 days. All values stayed significantly under this limit ($p < 0.05$). Only the uncased control magnet exceeded the limit clearly. After 28 days, the critical amount could still not be measured for any of the analyzed products. Comparing the release of corrosion products, there was no homogenous behavior within the product groups or among the prosthesis magnets, the abutments, and keepers after 1, 4, 7, and 28 days. All products showed an increase of corrosion from the first to the 28th day. A comparison of corrosion in regard to quantity on 7th and 28th day showed linear and nonlinear increases of corrosion products on the specimen.

Most of the dissolved ions were parts of the steel magnet caps and different corresponding ferromagnetic alloys for keepers. Highest solubility rates were attained by the elements iron and chromium. Palladium and cobalt were found as corrosion products with different keepers and implant abutments. In the case of the magnets of one manufacturer, low amounts of nickel were found as an alloy ingredient of the steel cap.

Studies on the biocompatibility of materials used in dentistry describe the potential influence of the elements found in this analysis on the human organism.[18] The effect of iron is discussed as being possibly mutagenic but not as being carcinogenic. Because of its corrosion stability, palladium has a very low mutagenic and carcinogenic potential, whereas cobalt is classified as possibly carcinogenic.[18] Wirz and Schmidli[22] and Haoka et al[25] found high concentrations of Fe ions, depending on the corrosion solutions used.

Titanium as a material for the encapsulation of magnets has good biocompatible properties.[14,22,34,42] Other materials used for the encapsulation of rare-earth magnets or for the production of keepers and implant abutments are different types of surgical steel. Austenitic and ferritic stainless steels are both highly corrosion-resistant. Ferritic stainless steels contain titanium and are less durable than austenitic grades. In the corrosion tests of products from ferritic stainless steel, Ti could be found. In this study, the detected titanium amounts originate from the encased magnets or had been alloy components of keepers and implant abutments. The solubility rates for titanium were comparatively low. This corresponds to the results of Wirz and Schmidli,[22] stating that there were only minor signs of corrosion on the titanium caps, even in FeCl solution. From the results of this investigation, it cannot be stated if the corrosion and especially the release of titanium found in the products from surgical steel occurred in the areas around laser-welded seams.

The general need to encapsulate rare-earth magnets in the mouth can be seen after measuring the corrosive properties of uncased SmCo magnets. Already on the first day, alloy components dissolved. The corrosion values clearly surpassed the limits of ISO standard 22674:2006 after 7 days. This demonstrated the effect of the applied corrosion solution and corresponds to the experiences of other authors.[22,29]

The heavy corrosion of the control specimen is a confirmation for the necessity to encapsulate rare-earth magnet systems in a tight cover.[16,21-24,33,34,41,43,44] In the present study, neodymium and boron ions could be detected as corrosion products on encased NeFeB prosthesis magnets in the product Magfit-IP-IDN dome type. This seems to be evidence for a corrosive decomposition of the magnet core. Riley et al[39] and Wirz and Schmidli[22] think that the reason may lie in a corrosive defect of the capsule or in the diffusion of the metal ions due to a loose joint of the capsule.

Because of the different magnetic systems, different magnetic alloys and capsules, different test conditions, time periods, and corrosion solutions and the nonstandardized and very different interpretation methods analyzed in previous studies, a direct comparison of the present test results with the results of previous authors cannot be realized. By use of ISO standard 10271:2001 as a test specification, comparability of the results of corrosion analyses should be possible.

Conclusion

Magnetic systems offer the possibility to functionally attach removable restorations on preserved teeth or dental implants. In the past, new products could be launched due to new manufacturing technologies and the further development of magnetic alloys and encapsulation materials. So far, a basic problem has been the susceptibility to corrosion of magnets and the corresponding ferromagnetic alloys in the oral cavity. In previous studies, several physicochemical analyzing methods were used. Standardized analyses corresponding to the test standard for the corrosion behavior of dental metals could not be found. The analysis of the corrosion behavior of modern magnetic attachments for use on teeth and dental implants according to ISO 10271:2001 showed that after 7 days, metal ions had dissolved on all specimens. In the product Magfit-IP-IDN dome type, the rare earth magnet corroded. For this product an improvement of the capsulation would be desirable. None of the products reached the allowed limit specified in ISO 22674:2006. All tested products seem to be suitable for dental application. Further studies in regard to the specific biocompatibility and possible cytotoxic effects on mucosa and tissue would be desirable.

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